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Method for operating a compression-ignition internal  
5 combustion engine

The invention relates to a method for operating a  
compression-ignition internal combustion engine in  
accordance with the preamble of claim 1.

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One objective in the development of new diesel internal  
combustion engines is to minimize the formation of  
exhaust gas emissions, in particular the emissions of  
nitrogen oxides. Exhaust gas recirculation is often  
15 used as a means for reducing the emission levels, with  
an exhaust gas recirculation rate being set as a  
function of the load point. A further drop in the  
nitrogen oxide emissions can be achieved by means of an  
SCR catalytic converter, in which the addition or  
20 metering of a reducing agent, e.g. ammonia, is  
implemented proportionally to the formation of nitrogen  
oxide in the internal combustion engine. The required  
safety devices only permit limited conversion rates in  
an SCR catalytic converter of this type, since the  
25 untreated nitrogen oxide emissions from the internal  
combustion engine can only be determined from known  
engine map data. Sensors for the direct measurement of  
the concentrations of nitrogen oxides or ammonia in the  
exhaust gas are still in the research stage, and the  
30 sensors which are currently available are still  
unreliable.

DE 197 34 494 C1 has disclosed a method for operating  
an internal combustion engine, in which a recirculation  
35 rate of the exhaust gas is calculated on the basis of a  
two-fold measurement of the oxygen concentration in the  
exhaust gas and in the charge air. In this method, in  
addition to the fact that the outlay on measuring

equipment is high, only the recirculation rate of the exhaust gas is determined.

5 EP 554 766 B1 has disclosed a method in which a metering device for an SCR catalytic converter is controlled. The knowledge of the untreated nitrogen oxide emission levels which is required for this purpose is obtained by using engine map data, which provide a relatively inaccurate description of the  
10 engine emission as a function of engine parameters. On account of the fact that the untreated nitrogen oxide emission level is only approximately known, considerable safety margins have to be built in to avoid a breakthrough of ammonia downstream of the  
15 catalytic converter, and consequently the conversion rate in the catalytic converter achieved is low, at up to approximately 70%.

DE 100 43 383 C2 has disclosed a method for determining  
20 the nitrogen oxide content in exhaust gases from internal combustion engines, in which the air mass fed to the internal combustion engine is recorded, with the combustion center of gravity being determined from at least one current measured value for the engine  
25 operation. The untreated NOx emissions are calculated from the value for the position of the combustion center of gravity and the values for the recorded fuel quantity and air mass. The parallel determination of air mass, fuel mass and recirculated exhaust gas mass  
30 entails considerable outlay.

The combustion center of gravity uses the first law of thermodynamics to describe the state in the combustion chamber in which 50% of the fuel energy introduced has  
35 been converted. The position of the center of gravity is the associated crank angle position, i.e. a crank angle position of the piston, at which 50% of the quantity of fuel participating in the combustion has

been converted into heat.

Therefore, the invention is based on the object of providing a method for determining or minimizing  
5 nitrogen oxide emissions.

According to the invention, this object is achieved by a method having the features of claim 1, claim 2 or claim 3.

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The method according to the invention is distinguished by the fact that a mean gas temperature in the cylinder is determined during a combustion operation in the combustion chamber, so that a gradient of the mean gas  
15 temperature is calculated, and the untreated nitrogen oxide emission level from the internal combustion engine is determined from a value for the gradient of the mean gas temperature and/or from a position of the gradient of the mean gas temperature in the combustion  
20 chamber. According to the present invention, the untreated nitrogen oxide emission level (NO<sub>x</sub> emission) formed in the compression-ignition internal combustion engine is directly related to the gradient of the mean gas temperature in the cylinder. Accordingly, the  
25 engine parameters are set in such a manner that a profile of the gradient with which lower NO<sub>x</sub> emissions are formed is produced during combustion.

Furthermore, the method according to the invention is  
30 distinguished by the fact that a mean gas temperature in the cylinder is determined during a combustion operation in the combustion chamber, so that the untreated nitrogen oxide emission level from the internal combustion engine is determined from a maximum  
35 value for the mean gas temperature in the combustion chamber and/or from a position of the maximum value for the mean gas temperature. According to the present invention, the untreated nitrogen oxide emission level

(NOx emission) formed in the compression-ignition internal combustion engine is directly related to the maximum value for the mean gas temperature in the cylinder. Accordingly, the engine parameters are set in  
5 such a manner that a defined maximum value is set during combustion or a predetermined maximum value is not exceeded. This allows simplified determination of the NOx emissions, in which the outlay on measurement technology is reduced.

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The method according to the invention is also distinguished by the fact that a mean gas temperature in the cylinder is determined in the combustion chamber, and the untreated nitrogen oxide emission  
15 level from the internal combustion engine is determined from a value for a mean gas temperature when the intake valve is closed and/or a value for a final compression temperature in the combustion chamber. According to the present invention, the untreated NOx emission level  
20 formed in the compression-ignition internal combustion engine is directly related to the value for the mean gas temperature which is determined prior to commencement of the combustion, at the instant at which the intake valve closes and/or at the end of  
25 compression. As a result, an accurate, simplified determination of the NOx emissions is achieved, so that the outlay on measurement technology is likewise reduced.

30 According to one configuration of the invention, the mean gas temperature is determined in a defined crank angle range. It is preferable to select a crank angle range in which the mean gas temperature in the cylinder has a virtually linear profile. This achieves accurate  
35 determination of the NOx emissions, since evaluation in a narrow crank angle range is reliable and less complex. Consequently, the outlay on measurement technology can be reduced.

In a further configuration of the invention, a quantity of a reducing agent for the downstream exhaust gas aftertreatment system is determined from the untreated  
5 nitrogen oxide emission level which has been determined. Accordingly, the exhaust gas aftertreatment is optimized and, by way of example, a metered quantity for an SCR catalytic converter is varied.

10 According to a further configuration of the invention, the metered quantity of fuel is injected into the combustion chamber in such a manner that a predetermined gradient of the mean gas temperature in the combustion chamber and/or a predetermined position  
15 of the maximum value for the mean gas temperature is established in the combustion chamber. Consequently, the mean gas temperature can be altered in such a manner that according to the invention the formation of the NO<sub>x</sub> emissions takes place at a minimal level or is  
20 as far as possible minimized. In this case, a predetermined rise in the gas temperature per unit time or a predetermined position of the maximum value is set. Accordingly, a predetermined maximum temperature value for the mean gas temperature, at which the  
25 formation of NO<sub>x</sub> emissions rises, cannot be exceeded.

According to a further configuration of the invention, the metered quantity of fuel is injected into the combustion chamber in such a manner that a combustion  
30 center of gravity is at a defined crank angle position. In this case, increased formation of NO<sub>x</sub> can be avoided.

According to a further configuration of the invention,  
35 an exhaust gas recirculation quantity for setting a defined oxygen concentration in the combustion chamber is set as a function of a combustion center of gravity. In this case, the required exhaust gas recirculation

rate is calculated from the determined untreated NOx emission level from the internal combustion engine, and the exhaust gas recirculation is adjusted until a defined oxygen concentration results in the combustion chamber.

In one configuration of the method according to the invention, a drop in the oxygen concentration which is required for nitrogen oxide reduction is calculated from the calculated untreated nitrogen oxide emission level, so that an exhaust gas recirculation device is set in such a manner that after combustion air has been mixed with recirculated exhaust gas a defined oxygen concentration is produced in a cylinder charge upstream of or in the combustion chamber. As a result, targeted and rapid control of the internal combustion engine is achieved at the respective load point, so that the formation of untreated NOx emissions is reduced. It is preferable for desired values for the oxygen concentration to be stored in an engine map of the internal combustion engine in the engine control device.

According to a further configuration of the invention, the oxygen concentration of the combustion air before it enters the combustion chamber is measured by means of an oxygen sensor, and a defined oxygen concentration of the combustion air upstream of or in the combustion chamber is set by means of the exhaust gas recirculation device as a function of the measured concentration. The use of the oxygen sensor brings about targeted and rapid control of the internal combustion engine to lower the formation of untreated NOx emissions at the respective load point.

In one configuration of the method according to the invention, the oxygen concentration of the exhaust gases after the exhaust gases have emerged from the

combustion chamber is measured by means of an oxygen sensor, the oxygen concentration of the combustion air before it enters the combustion chamber being calculated from this signal, an exhaust gas recirculation rate and a measured combustion air quantity, and a defined oxygen concentration of the combustion air upstream of or in the combustion chamber is set by means of the exhaust gas recirculation device as a function of the calculated concentration. As a result, targeted and rapid control of the internal combustion engine so as to reduce the formation of untreated NOx emissions at the respective load point, taking into account the last combustion operation, is achieved by the use of the oxygen sensor in the exhaust manifold.

Further features and combinations of features will emerge from the description. Specific exemplary embodiments of the invention are illustrated in simplified form and explained in more detail with reference to the following drawings, in which:

Fig. 1 shows a cross section through a cylinder of a direct injection compression-ignition internal combustion engine,

Fig. 2 diagrammatically depicts a mean gas temperature of an internal combustion engine shown in Fig. 1 as a function of a crank angle,

Fig. 3 shows a schematic diagram of a gradient for the mean gas temperature of the internal combustion engine shown in Fig. 1 as a function of the NOx emission,

Fig. 4 diagrammatically depicts the mean gas temperature when an intake valve of the internal combustion engine as shown in Fig. 1

is closed, as a function of the formation of NOx emissions,

- 5        Fig. 5 diagrammatically depicts the mean gas temperature at the end of a compression stroke of the internal combustion engine shown in Fig. 1 as a function of the formation of NOx emissions,
- 10      Fig. 6 diagrammatically depicts the maxima for a mean gas temperature in the combustion chamber as a function of the current untreated NOx emission level from an internal combustion engine as shown in Fig. 1,
- 15      Fig. 7 diagrammatically depicts the curve of an NOx reduction rate as a function of an exhaust gas recirculation rate, and
- 20      Fig. 8 diagrammatically depicts the curve of an NOx reduction rate as a function of an oxygen concentration in the combustion air of an internal combustion engine as shown in Fig. 1.
- 25      Fig. 1 illustrates a cross section through a cylinder block 1 of a compression-ignition internal combustion engine with direct injection. A piston 12 is guided displaceably in a cylinder 2, and the top side of this piston, together with a cylinder head 13, delimits a combustion chamber 11. An intake valve 14 and an exhaust valve 17 are arranged in the cylinder head 13, with the combustion air which is required being fed to the combustion chamber 11 through the intake valve 14 via an induction pipe 15. It is preferable for the
- 30      respective air mass to be recorded by an air mass measuring device 16, which is connected to an engine control device 6 via a line 22.
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Combustion gases pass through the exhaust valve 17 into an exhaust pipe 18, which leads to an exhaust gas aftertreatment device (not shown in the drawing). This exhaust gas aftertreatment device in particular  
5 includes an SCR catalytic converter for effectively lowering the NOx emission levels. Furthermore, an exhaust gas recirculation line 19 which branches off from the exhaust pipe 18 serves to recirculate combustion gases into the induction pipe 15. A flow  
10 meter 20 for recording the flow of exhaust gas which is recirculated and setting the quantity of exhaust gas which is recirculated is located in this exhaust gas recirculation line 19. The recorded quantity of recirculated exhaust gas is transmitted to the engine  
15 control device 6 via a line 21.

Furthermore, a pressure sensor 3, which transmits the pressure which is present in the combustion chamber via a connecting line 4 to the engine control device 6, is  
20 arranged in the combustion chamber 11, in the cylinder head 13. A fuel injection valve 25, which is connected to an injection pump 23 via an injection line 26, is also arranged in the cylinder head 13. A measuring apparatus 24 for recording the fuel quantity is  
25 provided between the injection pump 23 and the fuel injection valve 25. This fuel measuring device 24 is connected to the engine control device 6 via an electric line 27. The injection pump 23 is likewise connected to the engine control device by a control  
30 line 28.

It is preferable for an oxygen concentration of the combustion air fed into the combustion chamber 11 to be recorded by means of an oxygen sensor 29, which is  
35 preferably arranged in the induction pipe upstream of the intake valve 14 and is preferably connected to the engine control device 6 via a line 30. Alternatively, an oxygen sensor 29a is arranged in the exhaust pipe 18

or in the exhaust gas recirculation line 19.

The method according to the invention is aimed at minimizing the formation of NO<sub>x</sub> emissions during  
5 operation of the internal combustion engine and/or optimizing the exhaust gas aftertreatment. According to the invention, the fuel injection valve 25 is used to introduce a quantity of fuel which is dependent on load into the combustion chamber 11. During combustion, the  
10 profile of the mean gas temperature in the combustion chamber is determined, and a gradient  $dT/d\phi$  of the gas temperature in a defined crank angle window as shown in Fig. 3 is formed from this profile. In the context of the invention, this gradient is directly  
15 related to the formation of nitrogen oxide emissions from the internal combustion engine. In this context, it is preferable to evaluate a relatively narrow crank angle range, in which the mean gas temperature in the cylinder is virtually linear. In accordance with  
20 Fig. 2, a range of this type may, for example, be selected to be between 0°CA and 30°CA after top dead center. Depending on the inclination of this straight line in [ $^{\circ}\text{K}$ ]/[ $^{\circ}\text{CA}$ ], a current nitrogen oxide emission from the internal combustion engine is determined. The  
25 mean gas temperature is usually determined from the pressure profile of the combustion.

Fig. 3 illustrates this state of affairs based on the example of a change in the start of injection of fuel  
30 in the early direction, i.e. the fuel is injected into the combustion chamber at an earlier stage, so that with a higher temperature gradient achieved, the NO<sub>x</sub> emission is increased. If the fuel injection is implemented in such a manner that the temperature  
35 gradient produced becomes lower, a drop in the NO<sub>x</sub> emission in accordance with Fig. 2 is expected. Consequently, the untreated nitrogen oxide emissions from the internal combustion engine can be determined

from a value and/or a profile of the gradient for the mean gas temperature or from a maximum value for the mean gas temperature in the combustion chamber 11. Alternatively, in accordance with Fig. 4 and Fig. 2, it is possible to use a mean gas temperature  $T_{ES}$  to determine the NOx emission, which is determined at the instant at which the intake valve is closed. Furthermore, a mean gas temperature  $T_{KE}$ , which is determined at the end of the compression phase of the internal combustion engine, can likewise be taken into account for determining the NOx emission as shown in Fig. 5. According to the invention, this has produced very good correlations with respect to the nitrogen oxide emissions from the engine. Consequently, both signals can be used for additional determination of the NOx emission or as a plausibility check.

Optionally or as an alternative, an evaluation of the maxima of the mean gas temperature in the combustion chamber is used to determine the NOx emission, which likewise allows an excellent correlation to be established with respect to the current nitrogen oxide emission from the internal combustion engine. In accordance with Fig. 6, for example, an early shift in the combustion by way of the start of injection causes the NOx emission to increase.

In general, a relative reduction in NOx can be achieved by exhaust gas recirculation. Accordingly, the relative NOx reduction is directly related to the oxygen concentration of the cylinder charge. In accordance with Fig. 7, in the current state of the art, different percentage reductions in nitrogen oxides result from the same exhaust gas recirculation rates, depending on the load point of the internal combustion engine. By contrast, according to the invention the oxygen concentration of the cylinder charge is used as a measurement or control variable. Accordingly, a defined

oxygen concentration of the combustion air is then established in the combustion chamber 11. In accordance with Fig. 8, this is measured and used as a control and measurement variable.

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The present method is suitable in particular for diesel internal combustion engines, in which there is an apparatus for the recirculation of exhaust gas and/or a metering apparatus for metering reducing agent for exhaust gas aftertreatment in a downstream catalytic converter. The untreated NOx emission level from the diesel engine is calculated from the profile of the gradient for the mean gas temperature in a defined crank angle window, with the quantity of reducing agent for the downstream exhaust gas aftertreatment system then being determined therefrom. In addition, it is possible to check the untreated NOx emission from the maximum value for the mean gas temperature in the cylinder for plausibility. Then, the required NOx reduction rate with which an exhaust gas recirculation is set is calculated from the calculated untreated NOx emission. Accordingly, after the combustion air has been mixed with the recirculated exhaust gas, a defined oxygen concentration is set upstream or even in the combustion chamber 11. The desired value for the oxygen concentration may preferably be stored as a constant value in the engine map data.

Since, furthermore, the position of the combustion center of gravity influences the profile of the mean gas temperature during combustion, the injection of fuel can be carried out in such a manner that combustion takes place at a defined center of gravity position. At this defined center of gravity position of the combustion (desired center of gravity), which is stored in the engine control device 6, operation of the internal combustion engine is optimized in terms of consumption and the formation of NOx emissions is

likewise at a low level.

According to the present invention, the efficiency of the compression-ignition internal combustion engine is likewise directly related to the position of the combustion center of gravity. Therefore, the engine parameters, in particular the fuel injection parameters, such as injection point, duration of injection and injection cycle, are set in such a manner that the optimum position of the center of gravity is present during the respective combustion or during each combustion. The optimum position of the combustion or the desired combustion center of gravity can be determined for the respective internal combustion engine, for example on an engine test bench. This desired value is then stored in the engine control device 6 for the respective internal combustion engine.

The center of gravity position can be set or the current value can be adapted to the desired value by means of varying the start of compression ignition and/or by means of varying the fuel injection. As a result, targeted and rapid control of the internal combustion engine is carried out at the respective load point, so that the internal combustion engine is operated with a high efficiency combined, at the same time, with a drop in the NOx emission.

The pressure sensor 3 provided in the combustion chamber 11 is preferably used to record a pressure profile in the combustion chamber 11 during a working cycle and to transmit this pressure profile to the engine control device 6. The current center of gravity position of the combustion can be determined from the pressure profile recorded. The position of the center of gravity changes with respect to the crank angle if the combustion profile changes. An efficiency of the internal combustion engine, which is directly related

to the position of the combustion center of gravity, is determined with the aid of the engine control device 6 using the recorded pressure profile and the metered quantity of fuel for each working cycle. In this case, the combustion center of gravity can be calculated from the indexing of the cylinder pressure in combination with measurement of the piston position in the combustion chamber using the first law of thermodynamics. In accordance with the present invention, the untreated NOx emission level from the compression-ignition internal combustion engine is then determined with the aid of the data that have been recorded, so that the operating mode or setting of the exhaust gas aftertreatment device (not shown in Fig. 1) is optimized. In this way, the untreated NOx emission level from the internal combustion engine is determined quickly and accurately, for example in order to optimize a downstream exhaust gas aftertreatment device. Accordingly, if the combustion is suitably controlled, it is possible to minimize the formation of NOx emissions during combustion.

The untreated NOx emission level which has been determined from the internal combustion engine is used for the desired NOx reduction required, and the required oxygen concentration in the charge mass or the combustion air is determined from this information in accordance with Fig. 8. Accordingly, the exhaust gas recirculation quantity is controlled in such a manner that a defined oxygen concentration is established in the intake port 15 or in the combustion chamber 11. A desired value for an oxygen concentration is preferably stored in the engine control device 6 as a constant value or in engine maps. In this way, the NOx emission formed in the combustion chamber is reduced, and the exhaust gas aftertreatment provided for this purpose is optimized, so that in a downstream SCR catalytic converter, by way of example, the supply of a quantity

of  $\text{NH}_3$  can be implemented optimally with the aid of the present invention.

According to the invention, the oxygen sensor 29  
5 measures the oxygen concentration of the combustion air  
before it enters the combustion chamber. The exhaust  
gas recirculation device 20 is then controlled in such  
a manner, as a function of the measured concentration,  
that a defined quantity of exhaust gas passes into the  
10 induction pipe 15. As a result, a defined oxygen  
concentration is established in the combustion air  
upstream of or in the combustion chamber.  
Alternatively, if the oxygen sensor is arranged in the  
exhaust pipe 18, the oxygen sensor 29a can be used to  
15 measure the oxygen concentration of the exhaust gases  
after the exhaust gases emerge from the combustion  
chamber. The oxygen concentration of the combustion air  
before it enters the combustion chamber is then  
calculated from this signal, an exhaust gas  
20 recirculation rate and a measured combustion air  
quantity. Depending on the calculated concentration,  
the exhaust gas recirculation device 20 is then  
controlled in such a manner that a defined quantity of  
exhaust gas passes into the induction pipe 15, so that  
25 a defined oxygen concentration is established in the  
combustion air upstream of or in the combustion  
chamber.